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An engineering approach for effective cleaning exhaust air from livestock housing - A Review of Danish experiences of using partial pit air exhaust

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Abstract

Ammonia, dust and odour emission from livestock production system caused negative impact to atmosphere environment and local society. It is therefore important to find a cost-effective method to reduce these emissions effectively. Application of air cleaning methods including chemical and biological filter techniques has been proposed to be used to clean the exhaust ventilation air of confined livestock building. However, it requires large exhaust air cleaning capacity and consequently results in high cost of investment and operation of the system.

Aiming at reduction of emission and optimal indoor air quality of confined farm animal buildings, a concept of partial pit ventilation has been investigated in varied conditions in Denmark. The partial pit ventilation is based on the hypothesis that the most pollutant air can be removed by an extra air exhaust near to the pollution sources in pit head space. The room air exhaust is remained as a major ventilation exhaust and controlled via control computer according to indoor thermal conditions. The airflow rate of the partial pit air exhaust is designed and controlled as only a small portion of the designed maximum ventilation rate of the building. By cleaning the pit exhaust air only, the required capacity for cleaning unit will be much reduced.

The investigations in Denmark, mostly for growing-finishing pig housing, have shown that the partial pit air exhaust can remove 65-75% ammonia of the buildings in general by using a pit air exhaust rate in 10% of the designed ventilation capacity for the building.

This paper provides an overview of currently available investigation results of this partial pit exhaust system, including both numerical simulations and experimental investigations; to identify the important factors that may affect the system performances for removal of ammonia and other pollutants in the air; and to address the extension works that may be needed to applying the method in practical production scales.

Keywords: ammonia emission reduction, indoor air quality, partial pit ventilation, odour, hydrogen sulphide

1 Introduction

Ammonia, dust and odour emission from livestock production system caused negative impact to environment and local society. It is therefore important to find a cost-effective method to reduce ammonia and odour emission effectively from agriculture. Application of air purification methods including chemical and biological filter techniques has been proposed to be used to clean the exhaust air at ventilation outlets of confined livestock building. Research efforts have been put in for the development of effective purification systems (Melse et al., 2006; Ogink & Bosma, 2007; Ogawa et al., 2011; Zhao et al., 2011). However, such a solution requires significant investment and operation cost to treat the large amount exhaust air from modern livestock facilities.

Design and control of new ventilation system may provide a sustainable solution for reducing the negative environmental impacts of confined livestock productions by reducing ammonia, dust and odour emission. The primary goal of ventilation in livestock buildings is to remove the surplus heat produced by the animals to maintain the indoor climate suitable for animals and the production. Following the requirements for animals' wellbeing and impacts to environment, we should provide sustainable engineering solutions to achieve an optimal indoor air quality and minimised emission, the additional goal for confined livestock productions. That is a challenge.

Facing to the goal of optimal indoor air quality and reduction of emission from the animal buildings, a concept of partial pit air exhaust (PPAE) has been tested in varied conditions in Denmark (e.g., Pedersen et al., 2010; Saha et al., 2010; Pedersen & Jensen, 2010; Zhang & Kai 2014). General results were promising with ammonia emission reduction of 50-70% and improved indoor air quality measured in ammonia concentration reduction of 60-80%.

The PPAE is based on a hypothesis that the most pollutant air can be removed by an extra exhaust opening near to the pollution sources. The PPAE airflow rate is designed and controlled as only a small portion of the total designed ventilation capacity for the room (DVCR), which was often defined as 10% of the DVRC in most experiments reviewed in this article. By applying an effective air purification unit only to this pit exhaust air channel, the required capacity of the cleaning unit will be much reduced.

The objectives of this article are to provide an overview of currently available data of the investigation on the PPAE installation in livestock housing ventilation; to identify the important factors that may affect the system performances for removal of ammonia and other pollutants in the air; and to address the extension works that may be needed to applying the method in practical production scales.

2 Overview of the investigations for Partial Pit Air Exhaust (PPAE)

2.1 Concept of Partial Pit Exhaust Ventilation

The idea of using an extra air exhaust as differential ventilation to remove the part of most pollutant air from slurry pit headspace directly and treated with an air purification unit was suggested and described in a research project proposal (Zhang, 2006a; 2006b). The field experiments of application of this concept in growing/finishing pig production unit can be found in the reports by Pedersen & Kai (2008); Saha et al. (2010), Pedersen & Jensen (2010), Pedersen et al. (2010) and Zong et al. (2014). The concept was also extended to applications in naturally ventilated (NV) cattle buildings aiming at collecting pollutant air in NV buildings for cleaning treatment to gain emission reduction from NV housing (Zhang, 2008; Wu et al., 2008, 2010). To investigate the ammonia removal efficiency of the partial pit exhaust in naturally ventilated cattle buildings, a numbers of studies were conducted (Bjerg & Andersen, 2010; Wu et al., 2012a; 2012b; Rong et al., 2014).

2.2 Assessment of the system performances

The system performances PPAE for reduction of emission can be described in three different terms: (a) Removal ratio, which is defined the proportion of the contaminant removed via PPAE related to the total emission from the confined system; (b) total emission and reduction comparing to a reference setup without PPAE; and (c) total emission and reduction comparing to emission factors.

The removal ratio, defined as the proportion of contaminant removed via pit air exhaust, can be used as a possible quantity to express the effectiveness of PPAE systems, and is especially useful if comparable recordings with PPAE does not exit. The main disadvantage of using the removal ratio is that the quantity of the total emission of the housing system is not given directly, which is important to evaluate the system total performance. Therefore, the total emission should be provided wherever it is possible. In such case, the emission factor of a similar housing type could be used if it is available for comparison.

2.3 In mechanically ventilated growing/finishing pig buildings

Most of investigations and assessments of PPAE were conducted in mechanically ventilated growing/finishing pig buildings (Pedersen et al., 2010; Pedersen & Jensen, 2010; Saha et al., 2010).

2.3.1 Measurements

Pedersen et al. (2010) reported an investigation carried out in three experimental growing/finishing pig units during a winter period. Each units were equipped with different pen floor configurations (see table 1) and a ceiling exhaust. Unit 3 included a PPAE system with air extraction at the side of slurry pit under dunging area. Pit exhaust rates of 10% and 20 % of the designed ventilation capacity of the room (DVCR) were investigated and the results are summarized in table 1. Results showed that emission of ammonia and odour through the ceiling exhaust was 65-81 % lower from the system with pit exhaust than from the reference, Unit 2, without a pit exhaust. The concentrations at ceiling exhaust, Table 1, also reflect the room air quality in the systems with and without PPAE.

Table 1. Odour and Ammonia emission, indoor air concentration represented by the values at ceiling exhaust and total emissions from three growing/finishing pig units in different floor and ventilation configurations during a winter period reported by Pedersen et al (2010). Unit 2 is used as reference and the data in parentheses are the relative values in percentages refer to that of Unit 2.

	Unit 1	Unit 2	Unit 3	
Floor configuration:	58 % solid 42 % slatted	33 % drain 67 % slatted	67 % drain 33 % slatted	
Ventilation exhaust configuration:	ceiling only	ceiling only	ceiling and pit	
Floor opening ratio:	0.063	0.125	0.075	
Ceiling exhaust, m^3 pig^{-1} h^{-1}	NA	NA	NA	
Pit exhaust, m^3 pig^{-1} h^{-1}	0	0	10	20
Indoor air concentration - at ceiling exhaust: Ammonia: ppm Odour, OU_E m^{-3}	 7.65 (93) 1410 (52)	 8.25 (100) 2730 (100)	 5.2 (63) 1250 (46)*	 3.0 (36)
Emission through ceiling exhaust: Ammonia, g NH_3-N pig^{-1} d^{-1} Odour, OU_E s^{-1} LU^{-1}	 5.16 (102) 255 (61)	 5.04 (100) 415 (100)	 1.92 (38) 70 (34)	 0.96 (19) 43 (24)
Total emission: Ammonia, g NH_3-N pig^{-1} d^{-1} Odour, OU_E s^{-1} LU^{-1}	 5.16 (102) 255 (61)	 5.04 (100) 415 (100)	 5.28 (105) 125 (60)	 5.76 (114) 118 (57)
Removal ratio via PPAE: Ammonia Odour			 63.6% 44.0%	 83.3% 63.6%

*The data was not reported separately from the two pit exhaust levels.

The subsequent investigation was carried out during a summer period (Pedersen & Jensen, 2010), which included result from the three above mentioned units and from an additional unit also equipped with a pit exhausts system. This fourth unit had the similar floor opening area as unit 3, but the openings were slightly differently distributed in the floor, Table 2. In principle, the diffuse ceiling air inlet system (used in all four units) and pigs' locations mostly in resting drain floor area generated airflows in the pit directing from the dunging area towards the resting area of the pen. Consequently the highest pollutant concentrations were expected beneath the resting area and, therefore, in this investigation the pit exhaust extraction point were placed beneath the resting area. The results are summarized in table 2 and showed that emission of ammonia; hydrogen sulphide and odour through the ceiling exhaust were 58-93 % lower from the system with PPAE than that from the reference (Unit 2) without pit exhaust.

Saha et al. (2010) reported an investigation in a growing/finishing pig test room to compare the indoor air quality and ammonia emission between the setups with and without PPAE. In their setup, the pit air exhaust openings were at the end of slurry pit under dunging area and the floor configurations were 67% slatted and 33 drain floor at the end of the resting area in pens. The total floor opening ratio was 12.5%. The study was conducted using 30 pigs growing from 36 to 76 kg during four two-week periods. The PPAE system was on in period 2 and 4 and in these periods and the exhaust airflow rate was in 11-12 m3 pig-1 h-1. The reported ammonia emission is illustrated in figure 1 and showed that the ceiling emission were 40 % less in the periods where the PPAE was on compared to the periods where it was off. Air quality data based on measurement in ceiling exhaust indicated that room ammonia concentration was reduced 43% with PPAE comparing to that without PPAE. Unfortunately an increased animal weight, an increased ceiling ventilation rate and a decreased room temperature from period 1 to period 4 limits the possibilities to draw general conclusion from these results.

Table 2. Ammonia, Hydrogen sulphide and Odour emission, indoor concentration measured at ceiling exhaust and total emissions from four growing/finishing pig units in different floor and ventilation configurations during a summer period reported by Pedersen & Jensen (2010). Unit 2 is used as reference and the data in parentheses are the relative values in percentages refer to Unit 2.

	Unit 1	**Unit 2**	**Unit 3**		**Unit 4**	
Floor configuration:	58 % solid 42 % slatted	33 % drained 67 % slatted	67 % drained 33 % slatted		75 % drained 25 % slatted	
Ventilation exhaust configuration:	ceiling only	ceiling only	ceiling and pit		ceiling and pit	
Floor opening ratio:	0.063	0.125	0.075		0.075	
Ventilation rate:						
Ceiling exhaust, m^3 pig^{-1} h^{-1}	57.5	52.5	49	43	48	39
Pit exhaust m^3 pig^{-1} h^{-1}	-	-	10	20	10	19
Concentration - at ceiling exhaust:						
Ammonia: ppm	4.75 (57)	8.4 (100)	2.6 (31)	1.5 (18)	2.2 (26)	1.1 (13)
Hydrogen sulphide: ppb	10.5 (5)	222 (100)	87 (39)	70 (32)	22 (10)	30 (14)
Odour: OU_E m^{-3}	133 (63)	210 (100)	85 (40)	70 (33)	100 (48)	85 (40)
Emission through ceiling exhaust:						
Ammonia, g NH_3-N pig^{-1} d^{-1}	3.6 (63)	5.8 (100)	1.5 (26)	1.1 (19)	1.1 (19)	0.8 (14)
Hydrogen sulphide, mg pig^{-1} d^{-1}	8.4 (8)	109 (100)	33.6 (31)	7 (7)	7 (7)	10 (9)
Odour, OU_E s^{-1} LU^{-1}	31 (69)	45 (100)	16.5 (37)	19 (42)	19 (42)	14 (30)
Total emission:						
Ammonia, g NH_3-N pig^{-1} d^{-1}	3.6 (63)	5.8 (100)	4.2 (72)	4.7 (80)	4.7 (80)	5.6 (97)
Hydrogen sulphide, mg pig^{-1} d^{-1}	8.4 (8)	109 (100)	82 (75)	118 (108)	79 (73)	106 (97)
Odour, OU_E s^{-1} LU^{-1}	31 (69)	45 (100)	32 (72)	43 (96)	43 (95)	49 (109)
Removal ratio via PPAE:						
Ammonia			64.3%	75.8%	75.8%	85.3%
Hydrogen sulphide			58.8%	93.9%	90.9%	90.9%
Odour			48.4%	55.8%	55.3%	72.4%

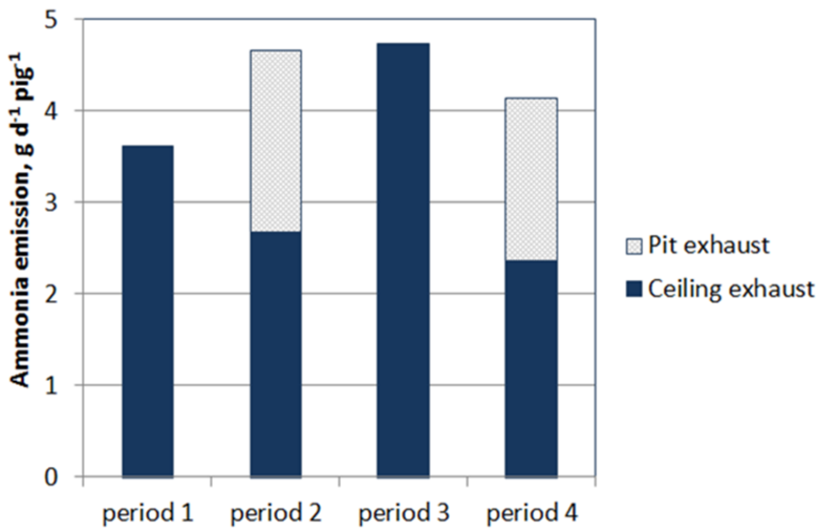

Figure 1. Ammonia emission from a pig growing room during four 2 weeks period, Saha et al. (2010).

Zong et al. (2014) reported the assessment of PPAE performances affected by two different air inlet configurations under summer condition in Denmark. It concluded that the inlet type can influence the airflow momentum and patterns in the ventilated room and further affect the removal ratio of PPAE for ammonia. Consequently, the indoor air qualities measured in ceiling exhaust concentrations were also somehow different. The summarised results of theirs investigation are presented in table 3.

Table 3. Assessments of PPAE performances in two pig section with different air inlets. (Zong et al., 2014)

	Section 1	Section 2
Floor configuration	67% slatted & 33% drain floor	67% slatted & 33% drain floor
Floor opening ratio	12.5%	12.5%
Ventilation inlet	Ceiling	wall
Ventilation exhaust configuration:	ceiling and pit	ceiling and pit
Ceiling exhaust, m^3 h^{-1} pig^{-1}	83.4	68.1
Pit exhaust, m^3 h^{-1} pig^{-1}	9.9	9.3
Ceiling / pit air exhaust temperature, °C	19.2 / 20.1	18.4 / 20.1
Outdoor air temperature, °C	14.3	14.3
Concentration - at ceiling/pit exhaust: Ammonia: ppm	2.1 / 16.6	3.4 / 21.3
Emission through ceiling/pit exhaust: Ammonia, g NH_3-N pig^{-1} d^{-1}	2.4 / 2.2	3.1 / 2.8
Total emission: Ammonia, g NH_3-N pig^{-1} d^{-1}	4.6	5.9
Ammonia removal ratio at PPAE	48%	47%

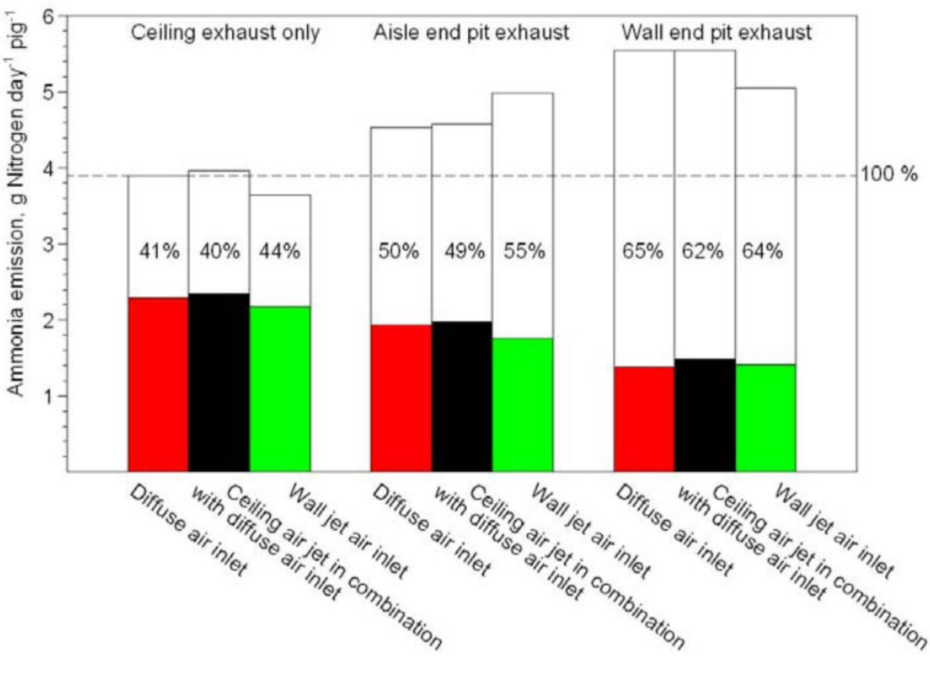

Figure 2. Daily mean ammonia emission after cleaning of 10% of DVCR (coloured bar) and without air cleaning (entire bar). The percentages in the bars show the cleaning effect compared to the configuration with diffuse ceiling air inlet and no air cleaning or pit exhaust (Bjerg & Zhang, 2013).

2.3.2 CFD simulations

Bjerg et al. (2008) have reported a CFD simulation results on efficiency of using partial pit exhaust in growing/finishing pig production unit. The simulation showed that by using 10% of DVCB as pit air exhaust connected with an air cleaning system can reduce the ammonia emission of the system by 73%. The ammonia concentration in the room is also significantly reduced. The assumed floor configuration were 33 % slatted floor and 67 % solid floor, and the slurry surface in the pit beneath the slatted floor were assumed to maintain a constant concentration. Based on the CFD simulation there will be increased ammonia release from slurry surface of 26% due to the pit ventilation.

Bjerg and Zhang (2013) reported a CFD simulation for varied ventilation system configurations including air inlet types and the location of PPAE openings using a PPAE rate of 10% DVCR. The floor configuration in this study were 67 % slatted floor and 33 % and one ammonia concentration where assumed on the slurry surface and another were assumed on the floor surfaces. Results showed by cleaning air of PPAE, ammonia emission can be reduced 49-65 %, and best results (62-65%) were obtained if the exhausts were located under resting area at end of the pit. It was found that using ceiling jet inlet in the warm periods caused a slightly reduced removal ratio of the PPAE. However, the total emission with PPAE were higher than with ceiling exhaust only, if the PPAE is not connected with an air cleaning equipment.

A further CFD investigation reported by Bjerg (2013) showed that the removal ratio of a PPAE can be increased by using some restriction plates in pit headspace to manipulate the air motion. The investigation showed that the plates in a system with diffusion ceiling inlet and with maximum ventilation may reduce the air moving up from the pit by 70 % and reduce the ammonia concentration in the ceiling exhaust by 40 %. A combination of 10 m-3 pig-1 h-1 PPAE and two plates in pit headspace is more effective than that of 20 m-3 h-1 pig-1 PPAE without plates.

2.4 In naturally ventilated buildings

2.4.1 Measurements

PPAE as an approach to collect pollutant air for cleaning treatment has been also proposed to integrate with naturally ventilated livestock buildings. Wu et al. (2010, 2012a) reported an investigation of the removal characteristics of PPAE in naturally ventilated cattle housing set-up by using wind tunnel and a 1:2 pit channel section with slatted floor, and using numerical modelling. They concluded that the removal ratio of a PPAE varied in 30-90% depending on the airflow conditions above the floor, floor opening ratio and exhaust opening locations. Optimal design of floor and exhaust locations may increase the removal efficiency of PPAE.

Rong et al. (2014) reported a field measurement in a dairy cattle building with natural ventilation and partial pit ventilation, named as hybrid ventilation. In this system, natural ventilation opening was controlled according to the indoor temperature, wind condition and rain. However, the partial pit ventilation was controlled in a constant level of 25% DVCR in summer period and further reduced in winter period when all natural ventilation opening became a minimum. The measurement results showed that, 64%-83% ammonia emissions were collected by the PPAE.

2.4.2 CFD Simulations

Bjerg & Andersen (2010) conducted a CFD simulation for a dairy cattle buildings section. The results indicated that a PPAE system, treating 80 m3 h-1 HPU-1 (HPU: heat production unit = 1 kW heat produced by animals at environmental temperature of 20 °C), on a yearly round Danish weather conditions has the potential to reduce ammonia emission with around 33% assuming fixed ventilation openings, and with controllable openings this figure will probably be above 50%.

Wu et al., (2012b) assessed the feasibility of using RANS (Reynolds – Averaged Navier–Stokes) turbulence models to evaluate the performance of a partial pit ventilation system to reduce gas emission under slatted floor. The accuracy of the three k-ε turbulence models (standard, RNG, realizable), the transition SST k-ω turbulence model and RSM (Reynolds Stress Models) were tested to predict the removal ratio by comparing to a laboratory measurement in wind tunnel. They found that RSM (Reynolds Stress Models) was the best of the used RANS turbulence models.

Bjerg et al. (2013) reported also the CFD assessment on indoor air temperature gradients for pig housing with hybrid ventilation that combined natural ventilation and mechanical PPAE under both summer and winter conditions. In this system, low ammonia emission was ensured by a mechanical PPAE system that operated in up to 20 percent of DVCR through openings in the slurry pits beneath the slatted floor. Low energy consumption was promoted by letting natural ventilation take care of the required air change beyond the capacity of the pit ventilations system. The report addressed some important issues and considerations for such housing design and ventilation control. The authors concluded that unequal adjustment of the openings in the two sides of the unit was an effective method to equalize the temperature the temperature distribution in the two sides of the unit. Their study was based on one single geometrical model that included possibilities to assume different position of ventilation flaps by changing the boundary condition (BC) for predefined faces from wall BC to interior or from interior to wall BC. They concluded that this was a labour effective method to investigate a large number of different setups, but after the investigation was completed they realized that some additional relevant positions of the flaps could have been foreseen and beneficially included in the geometrical model.

3 Discussions

3.1 Airflow rates of PPAE

The effect of airflow rates in partial pit air exhaust is straight forward, the higher the PPAE, the less gases will be remained in room and expelled via room ventilation while the room ventilation rate required will be also reduced. Using CFD methods Bjerg (2012) clearly demonstrated this relationship for ammonia emission from a growing pig unit, see Table 4. However, too high PPAE will increase the exhaust air cleaning capacity and it may induce unnecessary high air speed at emission surface and results in higher releasing rate of ammonia (Ye et al., 2009; Saha et al., 2010).

Table 4. Ammonia emission through ceiling exhaust in a system with PPAE at four total ventilations levels (10, 20, 40 and 100 m^3 h^{-1} pig^{-1}) the yearly fattening pig production conditions in Denmark - CFD estimation by Bjerg (2012) for a pig housing with 67 % slatted floor and 33 % drained floor

Ventilation rates:				
Maximum ceiling exhaust, m^3 pig^{-1} h^{-1}	100	90	80	60
Pit exhaust m^3 pig^{-1} h^{-1}	0	10	20	40
Relative emission through ceiling exhaust:	100	32	14	3

Investigations of the influence of increasing PPAE capacity was also conducted in the measurement by Pedersen et al (2010) and Pedersen & Jensen (2010), see Tables 1 and 2. For ammonia these measurement was very consistence with the theoretical and numerical simulated relationship. The measured effect of PPAE were largest during the winter period which should be expected because the air change required for maintain indoor climate is lower in the winter period and therefore the reduction of the ceiling exhaust becomes relatively larger. The expected increasing emission at increased pit exhaust was not found in the mentioned measurement for odour and sulphide hydrogen, Tables 1 and 2. The explanation could be that the pit exhaust was closed animals and their resting area and it may more effective for surplus heat removal. Consequently, the total ventilation was actually reduced, which resulted in the total emission unchanged or less than a conventional system with only ceiling exhaust. Anyhow, the data available is still limited at the current stage and therefore additional investigation is needed to determine the influence of the pit ventilation rate for the emission of these components.

3.2 Effect on total emission

PPAE is expected to reduce the concentrations of ammonia, sulphur hydrogen and other odour compounds close to the surfaces where the pollutants are released. Theoretically this will increase the concentration gradients above the release surfaces and, consequently, lead to an increased total emission. These relationships have been clearly demonstrated in CFD modelling assuming constant ammonia concentration on the releases surfaces (Bjerg & Zhang, 2013; Bjerg 2013). But this assumption properly exaggerates the effect because it ignore that the concentration on the release surface might depended on the on-going release, since a well-established release model is missing for the emission source-air boundary. The measured results presented in Tables 1 and 2 show that PPAE have a rather different influence on total emission, ranging from a 47 % reduction to a 26 % increase, and the diversity applies for all the mentioned pollutants. The sole systematically trend in the meas-

urement is that the total emission increases for both period and all pollutants when PPAE is increased from 10 to 20 m3 h-1 pig-1.
Saha et al. (2010) reported that total ammonia emissions were slightly increased when the PPAE system were on, but Figure 1 indicates that there might significant differences between period 2 and 4, where the total emission in period 4 was lower than that in period 3. Here, ventilation rate played a very important role.
The total emission data report by Zhang and Kai (2014), however, were lower than that given in Danish emission factor for average emission in similar pig housing without a PPAE, although the investigations were conducted in summer period when ventilation rate required was in maximum. Therefore, to avoid any increasing ammonia release at pit and floor surfaces, further investigation and assessments are needed.

3.3 Room airflow patterns

Airflow in the room will influence the air motion above the pen floor and consequently on the removal ratio of the pollutants via the PPAE. The actuate flow patterns are also dominated by inlet air jet momentum, ventilation configurations, animal's resting locations, indoor and outdoor thermal conditions.
Airflow patterns and animal lying behaviour and locations are related each other, since animal will choose some preferable location for lying where the buoyant force will be generated due to the heat produce by the animals to give an upward air motion, while the airflow patterns in room can create the comfort thermal condition or draft in animal zone which influences animals lying behaviours and locations.
In a room with diffusion ceiling inlet, the upward airflow above pig's resting area may occur due to the buoyant effect and results in downward airflow at the dunging area (if the room is configured as in Figure 3, in an symmetrical layout) when a ceiling jet inlet installed with a declined jet forcing the air motion to pig occupied zone, the flow pattern will changed totally.

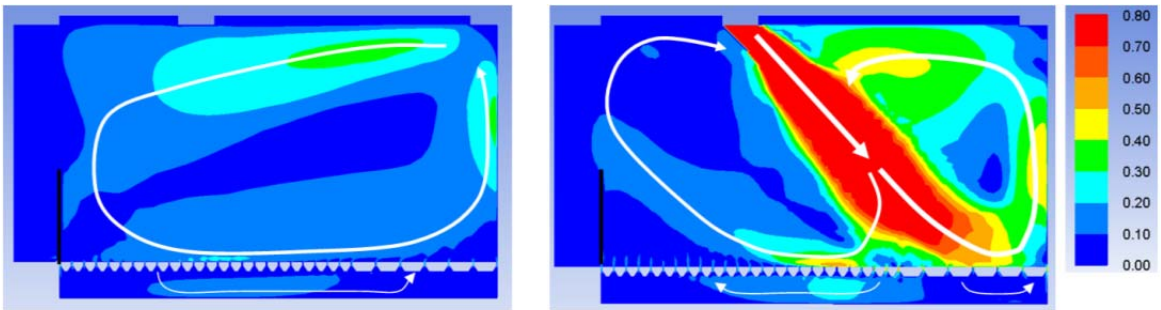

Figure 3. CFD prediction of air flow pattern and velocity (m s^{-1}) distribution in symmetry plane of a pig pen at outdoor temperature of 20 °C without PPAE. (a), Diffuse ceiling air inlet; (b), Diffuse ceiling air inlet in combination with ceiling air jet inlet (Bjerg & Zhang, 2013).

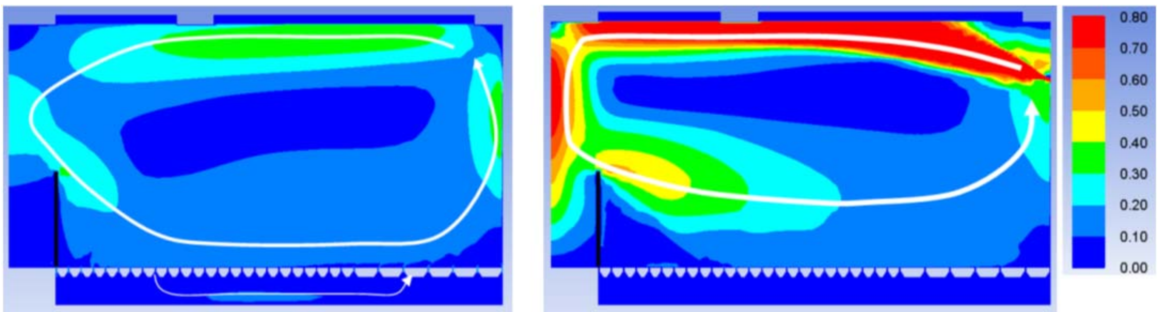

Figure 4. CFD prediction of air flow pattern and velocity (m s^{-1}) distribution in symmetry plane of a pig pen at outdoor temperature of 10 °C without PPAE: (a), Diffuse ceiling air inlet; (b), Diffuse wall jet inlet (Bjerg & Zhang, 2013).

In the cases with wall jet inlets, the airflow patterns in room are influenced by both inlet air momentums and inlet configurations, Figure 4. In fully rotated flow condition above pig pens, the optimal PPAE location may be identified accordingly.

In general, the airflow patterns are influenced by inlet types and locations; the flow momentum above floor influenced by ventilation rates / supply air momentum, which consequently on removal ratio of PPAE.

3.4 Effects of slatted floor openings

The pen floor opening ratio can affect the mean downward air speed from AOZ into the pit headspace. The less floor openings, the higher the mean air speed downward is, which can influence the removal ratio too. Therefore it is feasible to investigate where in the pen floor openings are essential and if they were dispensable without compromising the pen hygiene, and this way lead to an increased effectiveness of PPAE.

Following the growth of pigs, the lying area in pig pens will increase and that will result in a reduction of floor opening and increasing mean downward airspeed. The later will affect the removal ratio of the PPAE. However, the investigations reported under related subjects are still limited. Therefore, further investigations including full scale laboratory tests, CFD simulation are still essential and needed.

3.5 Effects of animal lying areas

Behaviours and lying patterns of pigs in pens influence air motion in AOZ as well as total flow patterns in room. There are two relevant factors: (1) the lying pigs results in actual reduction of floor opening area; (2) the buoyant airflow momentum generated by the pigs can potentially influence the total airflow pattern in room, and the effects will be varied due to pigs' lying patterns and locations. These factors will finally affect air exchanges between air in AOZ and in pit headspace.

Very limited information on that was reported in the previous investigations. Therefore, further investigations in controlled laboratory condition using artificial pigs and applying CFD simulation method will be essential to provide us some knowledge on that.

3.6 Effects of PPAE opening position

Investigation in both measurements (Pedersen & Jensen 2010) and CFD simulation (Wu et al., 2012b; Bjerg & Zhang, 2013) showed that the removal ratio were different comparing the exhaust opening locations under resting area and dunging area in a pen (see Figure 2). But detailed investigation on pit air exhaust opening configurations has not been conducted so far. Removal ratio under varied opening configurations can be further investigated using CFD method and experiments a full scale experimental room.

4 Conclusions

PPAE is an effective engineering approach to reduce emission by combining an effective exhaust cleaner. The system can significantly improve the indoor air quality, since the concentrated pollutants in air are removed via PPAE.

The removal ratios of the PPAE are influenced by airflow pattern, rates of PPAE, and locations of PPAE openings in pit headspace and therefore configuration and control of ventilation systems are crucial for system efficiency. Besides, slatted floor openings as well as animal lying behaviour and location can also influence the removal ratio for a PPAE.

To achieve optimal design and control of the system, further systematically investigations, both experimental and numerical, are still needed.

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